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DETAILED GEOID COMPUTATIONS FOR GEOS-C ALTIMETER EXPERIMENT AREAS

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ABSTRACT

The GEOS-C spacecraft is scheduled to carry onboard a radar altimeter for the purpose of measuring the geoid undulations in oceanic areas. An independently derived geoid map will provide a valuable complement to these experiments. This paper presents a detailed gravimetric geoid for the Atlantic and North East Pacific Ocean areas based upon a combination of the Goddard Space Flight Center GEM-6 Earth Model and surface $1^\circ \times 1^\circ$ gravity data. As part of this work a number of satellite derived gravity models were evaluated to establish the model which best represented the long wave length features of the geoid in the above mentioned area. Comparisons of the detailed geoid with the astrogeodetic data provided by Rice of the National Ocean Survey and dynamically derived tracking station heights indicate that the accuracy of this combined geoid is on the order of 2 meters or better where data was dense and 5 to 7 meters where data was less dense.

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DETAILED GEOID COMPUTATIONS FOR GEOS-C ALTIMETER EXPERIMENT AREAS

1. INTRODUCTION

The GEOS-C spacecraft is scheduled to carry an altimeter for the purpose of measuring the geoidal undulations in the oceanic areas. An independently derived geoid map will provide a valuable complement to these experiments.

This paper presents a detailed gravimetric geoid for the area of 180° to 340° East Longitude and 0° to 80° North Latitude based on a combination of the GSFC GEM6 Earth Model and 1° by 1° surface gravity data. One of the error sources encountered in gravimetric geoid computations is long wavelength geoid representation of the base gravity model. In the course of this computation, a number of satellite gravity models published in the past few years have been considered. Differences in detailed geoid heights computed with these various gravity models are generally less than 5 meters for areas with relatively dense surface gravity data coverage. However, in areas where surface data was lacking or sparce, differences are as large as 25 meters.

To assess the accuracy of the geoids computed, comparisons were made with astrogeodetic geoids and dynamically derived station heights.

2. METHOD OF COMPUTATION

The method of computation is presented in detail in Reference 1. The detailed geoid heights computed in this paper are based upon a combination of satellite

and surface 1°-by-1° gravity data. The satellite geoidal information is derived as a function of spherical harmonic coefficients of the gravity model and the surface geoidal heights are derived by incorporating surface 1°-by-1° gravity data into Stoke's equation for areas 20°-by-20° centered at the computational points.

The surface gravity data used in these computations consisted of 23,947 records of 1°-by-1° mean free air gravity anomalies obtained from the Defense Mapping Agency/Aerospace Center. This data was augmented with collections from the Nation Oceanic and Atmospheric Agency, the Hawaii Institute of Geophysics, the Lamont-Doherty Observatory, the Wood's Hole Oceanographic Labortory and other smaller sources.

3. ANALYSIS

3.1 Inter-Model Comparisons

As mentioned in Section Two of this report, detailed geoids were computed using the GEM 4, 5, 6 series, the SAO II, III series and the Rapp 1973 gravity Model. A brief description of these models follows.

GEM 4[2] is a combination solution consisting of (1) a satellite solution based upon 400,000 optical, laser, and electronic observations on 27 satellites including low inclination data from SAS and PEOLE (GEM3) and (2) 1707 5°-by-5° equiangular mean gravity anomalies based on 21,000 1°-by-1° surface gravity observations. The GEM 4 model is complete to degree and order 16 with additional terms to degree 22.

GEM 5[3] is a satellite solution based on the same satellite data set as the GEM 4 model but with different relative weighting for the electronic and optical data plus BC-4 geometrical data. GEM 5 is complete to degree and order 12 with additional terms to degree 22.

GEM 6[4] is a combination model consisting of (1) a satellite solution (GEM 5) and (2) Rapp's 5° equal area mean gravity anomalies based on 26,000 1°-by-1° surface gravity values. GEM 6 is complete to degree and order 16 with additional terms to degree 22.

SAO II[4] is a combination model consisting of (1) satellite solution based on optical and laser data obtained from 21 satellites and (2) 935 5°-by-5° equal area gravity anomalies derived by Kaula (1966)[5]. This model is complete to degree and order 16 with additional terms to degree 22.

SAO III[6] is a combination model consisting of (1) a satellite solution based on optical, laser, and Deep Space tracking data obtained from 25 satellites and (2) a similar set of surface gravity data as the SAO II model. This model is complete to degree and order 18 with additional zonal terms to degree 36 and resonant terms to degree 24.

Rapp[7] is a combination model consisting of (1) a satellite solution GEM 3 and (2) 1283 5°-by-5° equal area anomalies based on 23,355 1° x 1° surface

gravity anomalies. This model is complete to degree and order 20 with additional terms to degree 22.

The detailed geoids computed with these models were intercompared along profiles 40°, 20°, and 35° N latitude (Figures 1 through 3). The profile at 40° N extending from longitude 180° to 240° East and the profile at 20° N extending from longitude 280° to 340° East were especially chosen because of their location relative to the GEOS-C altimeter experiment calibration site. The profile at 35° N extending from longitude 180° to 340° East seemed to be the best general representative line. The curves of these profiles at the above mentioned latitudes indicate an envelope of 5 meters however, individually, differences are as large as 10 meters (Figure 1). For example, at longitude 180°E the SAO II curve is higher than the average by 5 meters and the GEM 5 curve is lower by an amount equal to 5 meters. At longitude 210° E the order reverses whereby GEM 5 is higher by 2 meters and SAO II is lower by 4 meters. The models show the largest scatter at 220° E longitude.

In Figure 2 the scatter at the Puerto Rico trench site is approximately 3 meters between GEM 5 and SAO II, III. Along the rest of this profile the scatter is on the average equal to 5 meters. Even though the scatter is about 5 meters, the slopes in many areas are generally quite similar, for example, in Figure 2 from 300° to 340° longitude. Thus relative geoid heights are probably known to better than 5 meters. Figure 3 however, shows that the SAO III results are rotated about the average curve by 3 meters at longitudes 200°E, 255°E, and 315°E.

These profiles in the Northern Hemisphere, basically located in areas of relatively dense surface gravity coverage, encompass only a small area of the globe. In order to better display the differences on a global basis where surface data is generally sparce and long wavelength contributions of the gravity models dominant, Figures 4 through 8 present contour plots of differences between the various models with GEM 6 adopted as the base model. All the plots show large differences in the Southern Hemisphere versus the Northern Hemisphere except in Australia where the differences are in the order of 2 meters due to the surface gravity constraint on the models.

A pattern of large differences extending along the length of North and South latitudes in the region of longitude 140° East to 200° East is apparent in all the plots. This pattern coupled with the dominant large differences in Southern Hemisphere is attributed to a lack of surface gravity data in these areas. These large differences exhibit a wavelength of about 40° in longitude, indicating variations in the low degree and order coefficients of the various models. The maximum differences at this wavelength are:

GEM-6 vs.	Maximum Geoid Height Difference
SAO III	54 meters (-28 to +26)
SAO II	32 meters (-14 to +18)
Rapp	18 meters (-8 to +10)
GEM 4	24 meters (-10 to +14)
GEM 5	8 meters (-4 to +4)

R. M. S. differences have also been calculated and are as follows:

GEM-6 vs.	R. M. S. Difference in Geoid Heights
SAO III	6.5 meters
SAO II	4.5 meters
GEM-4	3.7 meters
Rapp	2.7 meters
GEM-5	1.1 meters

One might conclude from the r. m. s. differences that all geoids are similar, however, it is felt that global r. m. s. differences are probably not too meaningful since the differences in the southern hemisphere are generally much larger than in the northern hemisphere. Furthermore, these relative differences could be interpreted as a lower bound for the absolute accuracy of the geoid. Figures 9.1 through 9.5 present the geoid height differences in histogram form. As is noted in these histograms, the most frequent differences are in the range of -5 to +5 meters.

3.2 Comparison With External Data

In order to establish the base model for detailed geoid computations for the test area, comparisons were made between the detailed geoids computed with the forementioned gravity models using the same surface gravity data base and astro-geodetic data in North America. Comparisons were also made with dynamically derived tracking station geoid heights.

3.2.1 Comparison With Astrogeodetic Data—Comparisons were made with Rice's[8] astrogeodetic geoid for a profile at latitude 35° N. The astrogeodetic data were first transformed (using 3 translational elements) to the center-of-mass system before any comparisons were made. Table 1 presents the differences between Rice's geoid and detailed geoids computed using the various models.

The differences in the geoid heights for all models were random except for SAO III and GEM 6 where an additional constant value of 2 meters for SAO III and 1 meter for GEM 6 had to be added. The agreement between Rice's geoid and all the models was on the order of ±2 meters.

3.2.2 Comparison With Dynamic Station Heights—Goddard Space Flight Center Long-Arc Orbital Analyses have provided geocentric coordinates for tracking stations (Marsh et al, 1973). Geoid heights derived from this solution were compared with the detailed geoid heights. Table 2 presents the results of these comparisons. All the models give similar results except for SAO III where differences as large as 5 meters versus the average are apparent. The r. m. s. agreement for all models is ±3 meters. This agreement is considered excellent considering the various error sources inherent in this type of comparison. For example, errors can be attributed to:

a. dynamically derived station heights

b. mean sea level values

c. gravimetric geoid heights

3.3 Goddard Earth Model (GEM 6) Detailed Geoid

Based on the discussions of the preceeding section, the GEM 6 gravity model was chosen to be the base model for detailed geoid computations in the area of longitude 180° to 340° East and latitude 0° to 80° North. This detailed geoid is presented in Figure 10.

The parameters used in the computation of the detailed geoid are:

$W_o = 6263687.5$ kgal m

$\gamma_e = 978032.2$ mgal

$a_e = 6378.142$ km

$1/f = 298.255$

$GM = 3.986009 \times 10^5\ km^3/sec^2$

$\omega = 0.72921151467 \times 10^{-4}$ rad/sec

4. CONCLUSIONS

The scatter in geoid height values derived from these models in areas of relatively dense surface gravity data is approximately 5 meters.

The SAO III gravity model shows the most prominent divergence from the general trend expressed by the other models where surface data were dense.

Greatest divergences in these models appeared in areas of sparce surface data coverage, notably the Southern Hemisphere. The magnitude of these differences was as large as ±25 meters with a wavelength of approximately 40°. This may

in part be due to the fact that satellite orbital perturbations arising from coefficients having this wave length are on the order of a few meters, making an accurate solution for the values difficult. It is felt that the new data types such as altimetry and satellite to satellite tracking will provide a great advance in the knowledge of the geoid, expecially in areas with sparce surface gravity coverage and with limited tracking station coverage.

GEM 6 was used as the base model for geoid computations primarily for two reasons.

a. The GEM 6 model encompassed the latest set of surface gravity data in its solution.

b. Comparisons with astrogeodetic geoids and dynamic station heights yielded similar results to those obtained using GEM 4 and RAPP 1973 models.

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Table 1

Profile at Latitude 35°N

Difference Between Rice's Converted Astrogeoid and Detailed Geoid Computed Using Various Models (meters)

Long. (deg.)	Rice	GEM-4*	GEM-5*	GEM-6*†	SAO-II*	SAO-III*††	RAPP*
81	-34	-1	-1	-2	-2	-2	-1
83	-30	1	1	0	0	-2	1
85	-32	-1	-1	-1	-2	-2	-1
87	-29	0	1	0	-1	-2	0
91	-29	0	2	1	0	-2	0
92	-29	0	2	2	0	-1	0
93	-31	-1	1	1	-1	-1	-1
96	-29	2	3	3	1	-1	2
99	-28	1	1	1	0	0	1
101	-28	0	1	1	0	1	1
105	-20	1	2	2	2	3	3
107	-21	0	0	0	0	2	1
110	-23	0	-1	-1	0	2	1
113	-27	0	-1	-1	-1	2	0
115	-30	1	-1	-1	0	1	0
117	-31	2	2	1	2	2	2

* Rice minus GEM-4 detailed geoid height, GEM-5, ...

† Systematic difference of one meter has been added

†† Systematic difference of two meters has been added

Table 2

Comparisons Between Dynamic Station Heights and Gravimetric Geoid Using Various Models (Meters)

Station No.	Lat. (deg)	Long. (deg)	GSFC 73* Long Arc	GEM-4†	GEM-5†	GEM-6†	SAO-II†	SAO-III†	
1032	48	307	12	-1	0	0	5	1	1
1021	38	283	-43	-9	-10	-10	-9	-14	-9
1022	27	278	-29	2	1	1	-1	-3	1
1030	35	243	-30	5	3	3	2	3	3
1034	48	263	-27	1	-1	-1	-3	-3	2
1042	35	277	-34	-2	-3	-3	-4	-7	-3
7036	26	262	-27	-2	-3	-3	-3	-5	-2
7037	39	268	-35	-1	-1	-1	-2	-6	-1
7050	39	283	-40	-6	-8	-8	-6	-12	-6
7045	40	255	-18	0	-1	0	1	-2	-1
9001	32	253	-22	1	0	1	6	1	2
9021	32	249	-30	-1	-3	-2	-8	-2	-1
7072	27	280	-32	4	1	0	-1	-2	1
7075	46	279	-32	5	4	5	5	1	6
7039	32	295	-35	4	6	4	6	2	6
7040	18	294	-46	4	5	4	2	3	3

* Geoid Height = (Dynamic height above ellipsoid) minus (Mean sea level height)

† GSFC '73 (Marsh, Douglas, and Klosko, 1973) minus GEM-4 detailed geoid, GEM-5, ...

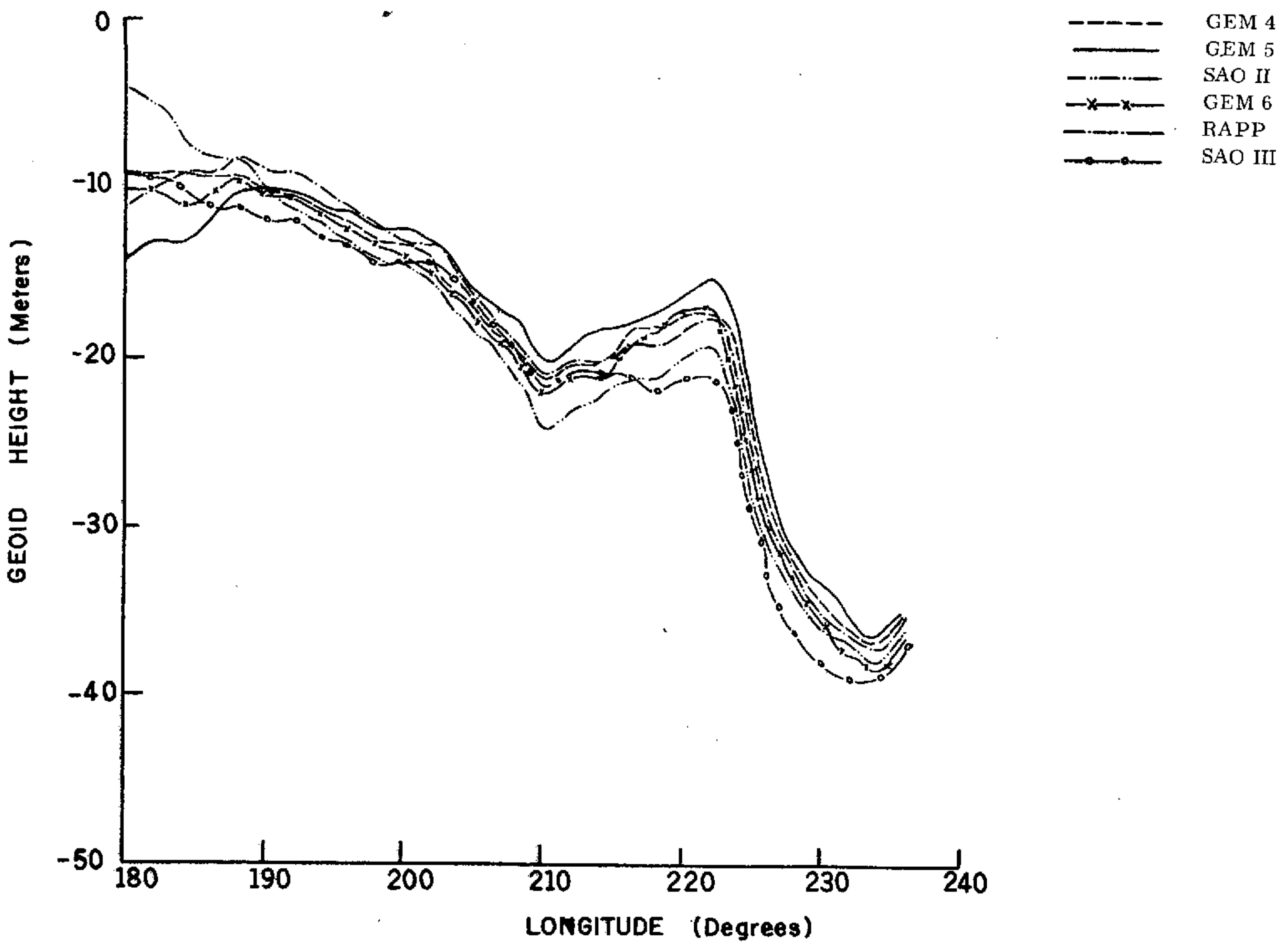

Figure 1. Detailed Gravimetric Geoid Profile Latitude 40°N

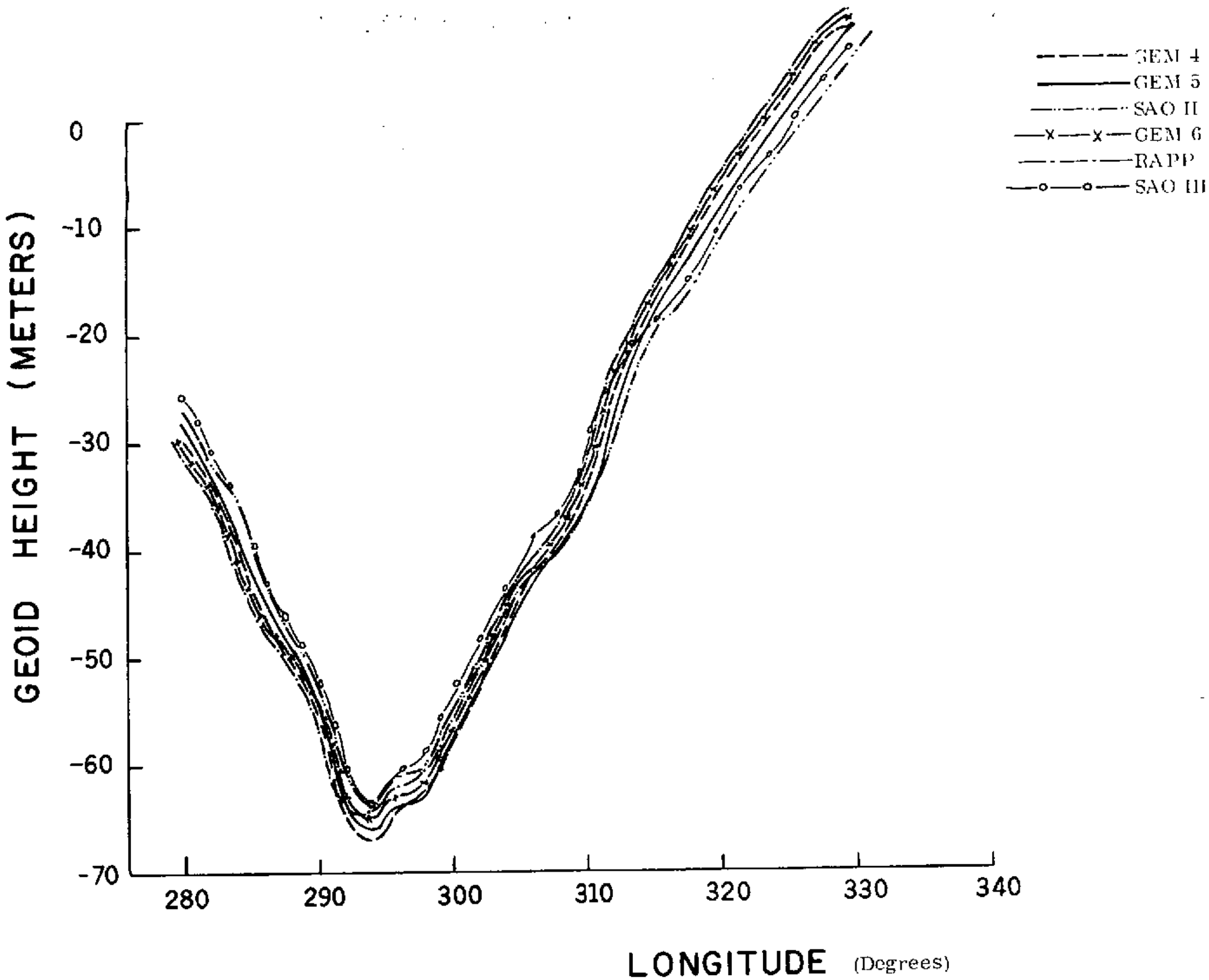

Figure 2. Detailed Gravimetric Geoid Profile Latitude 20°N

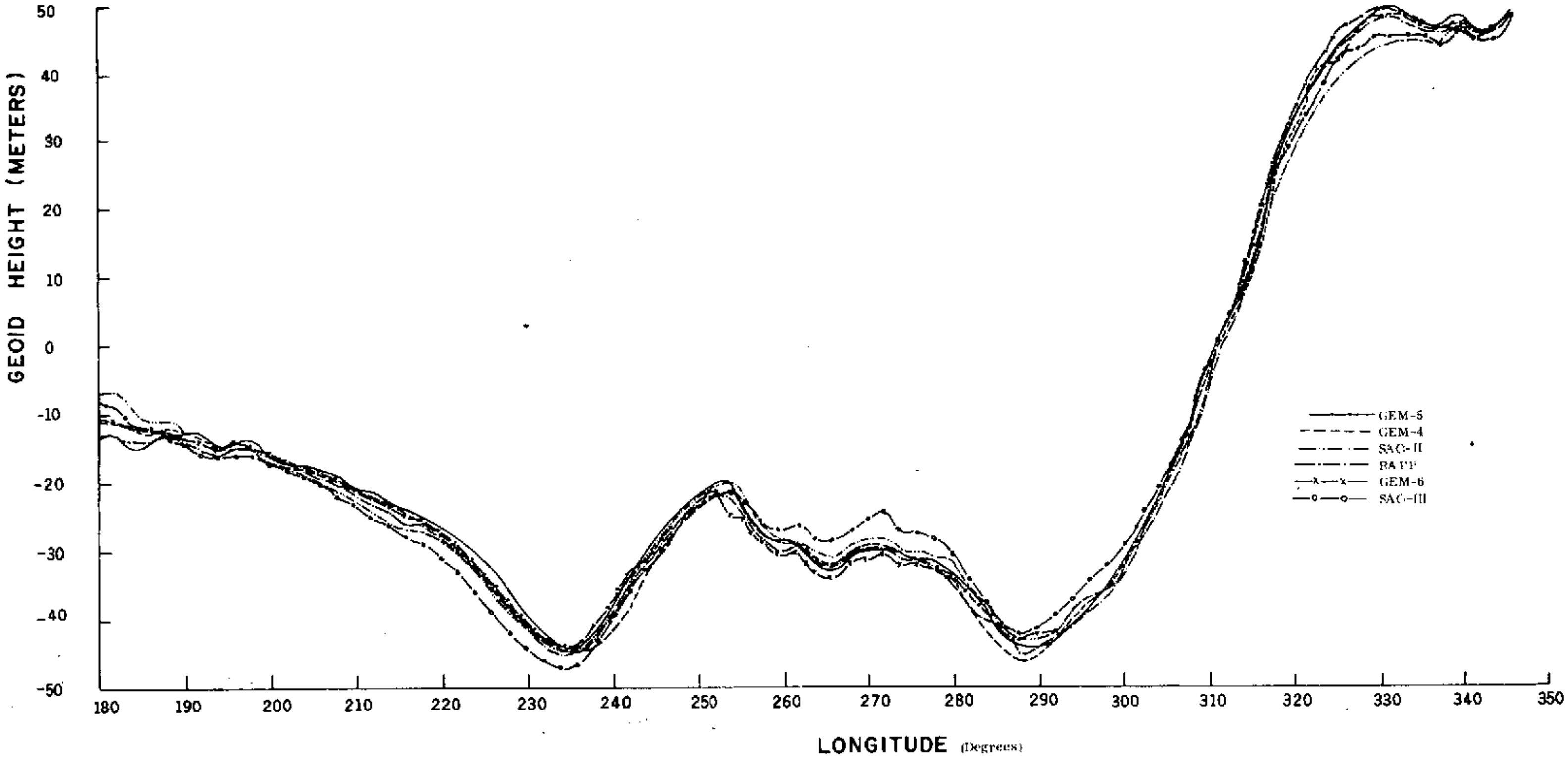

Figure 3. Detailed Gravimetric Geoid Profile Latitude 35°N

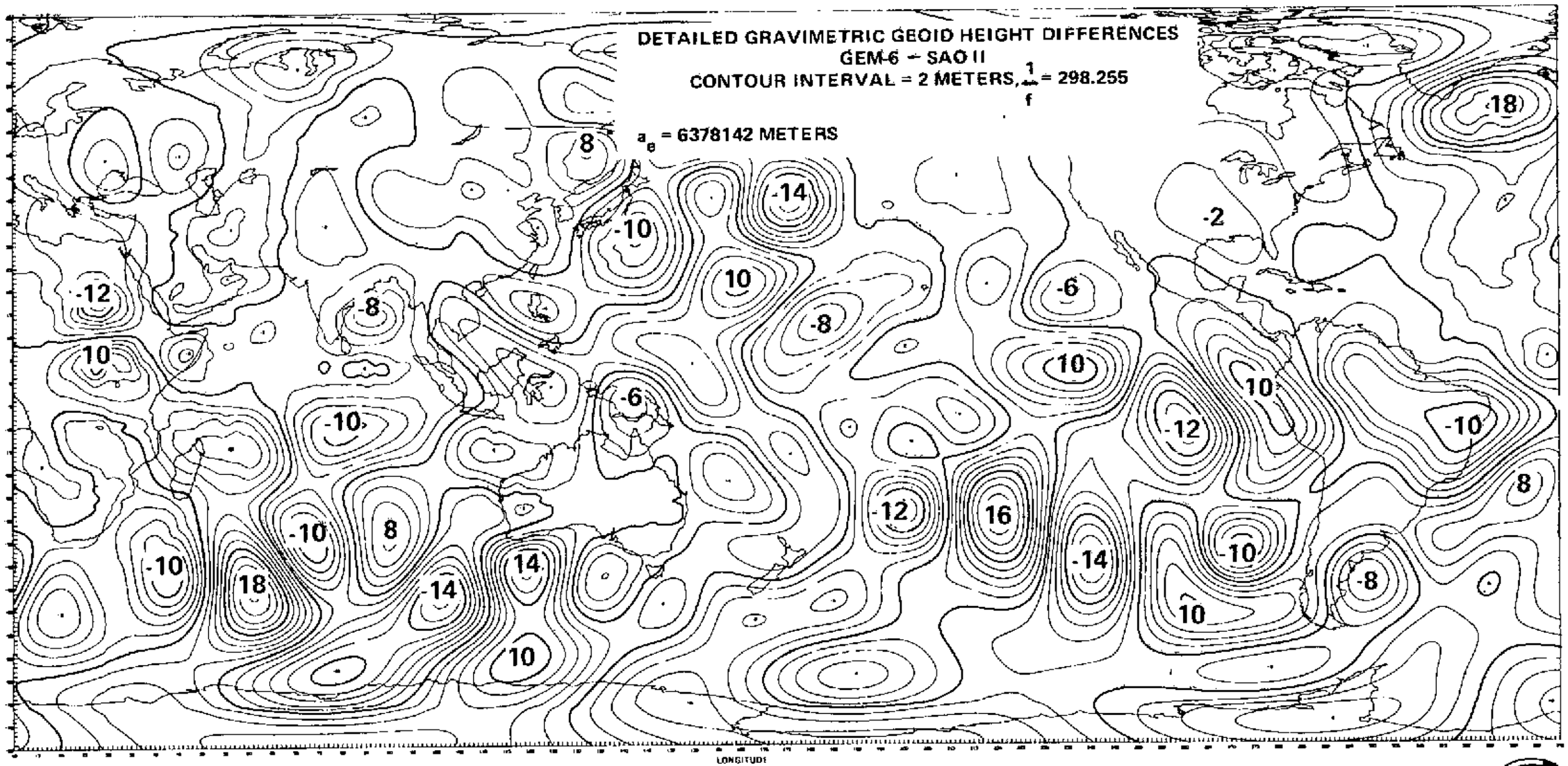

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Figure 4.

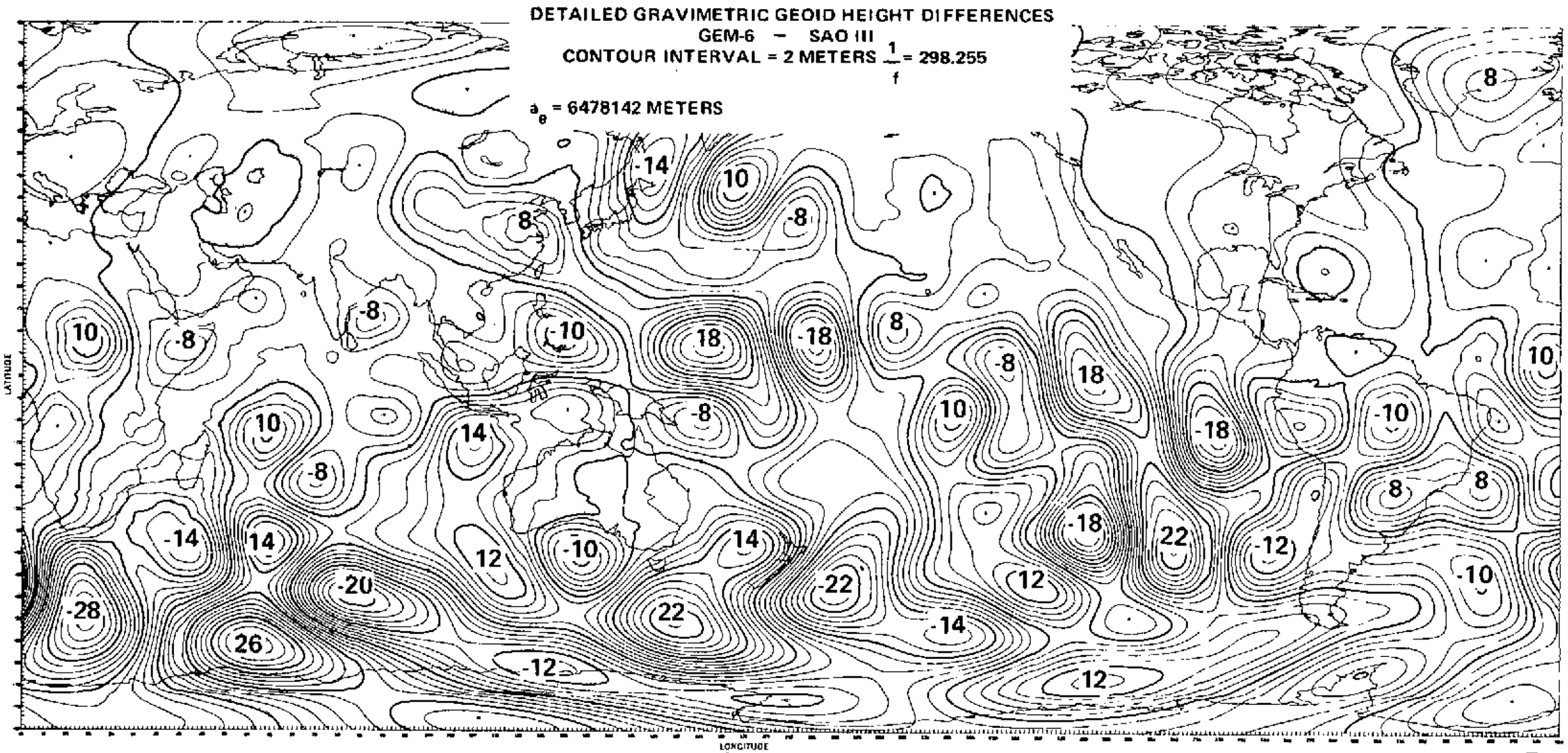

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Figure 5.

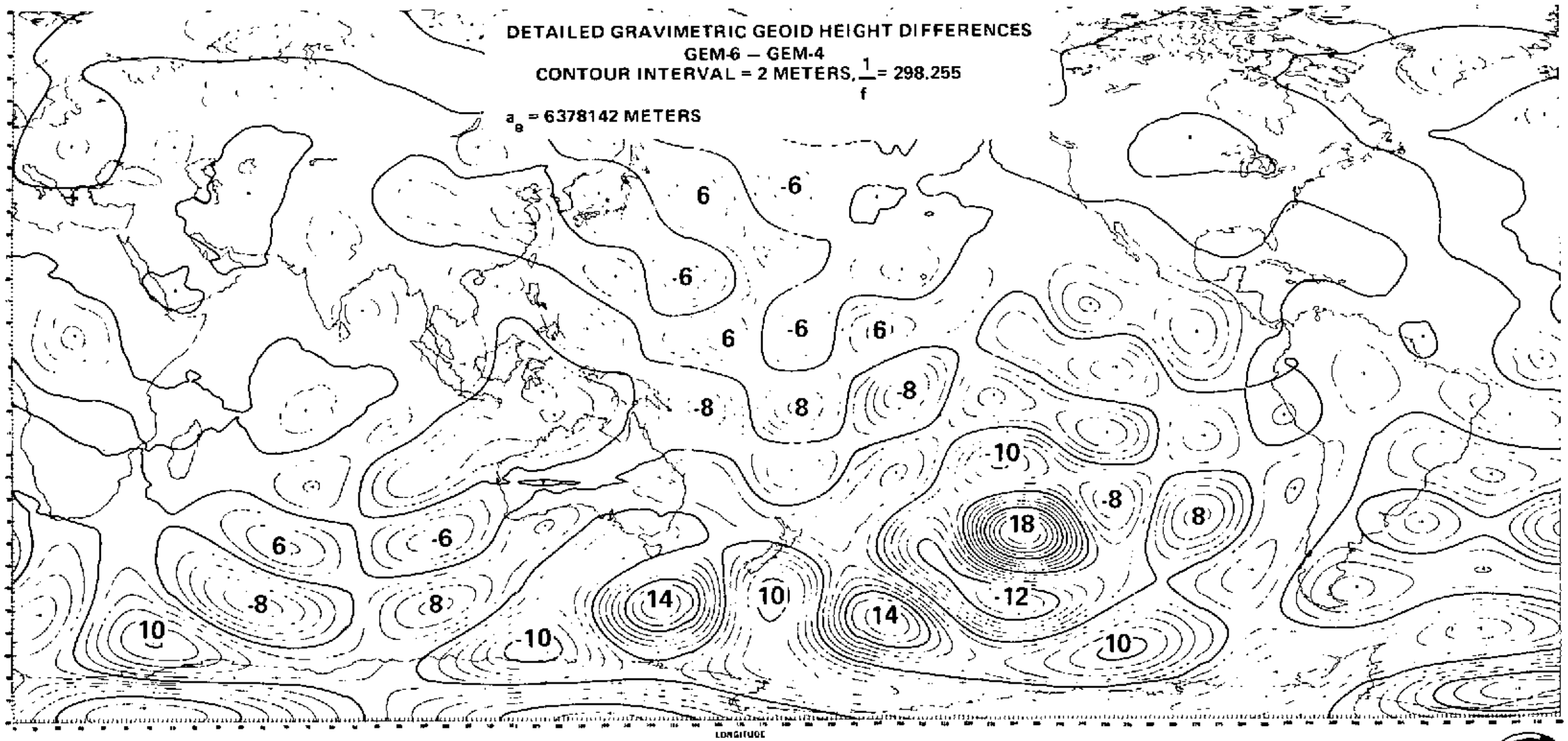

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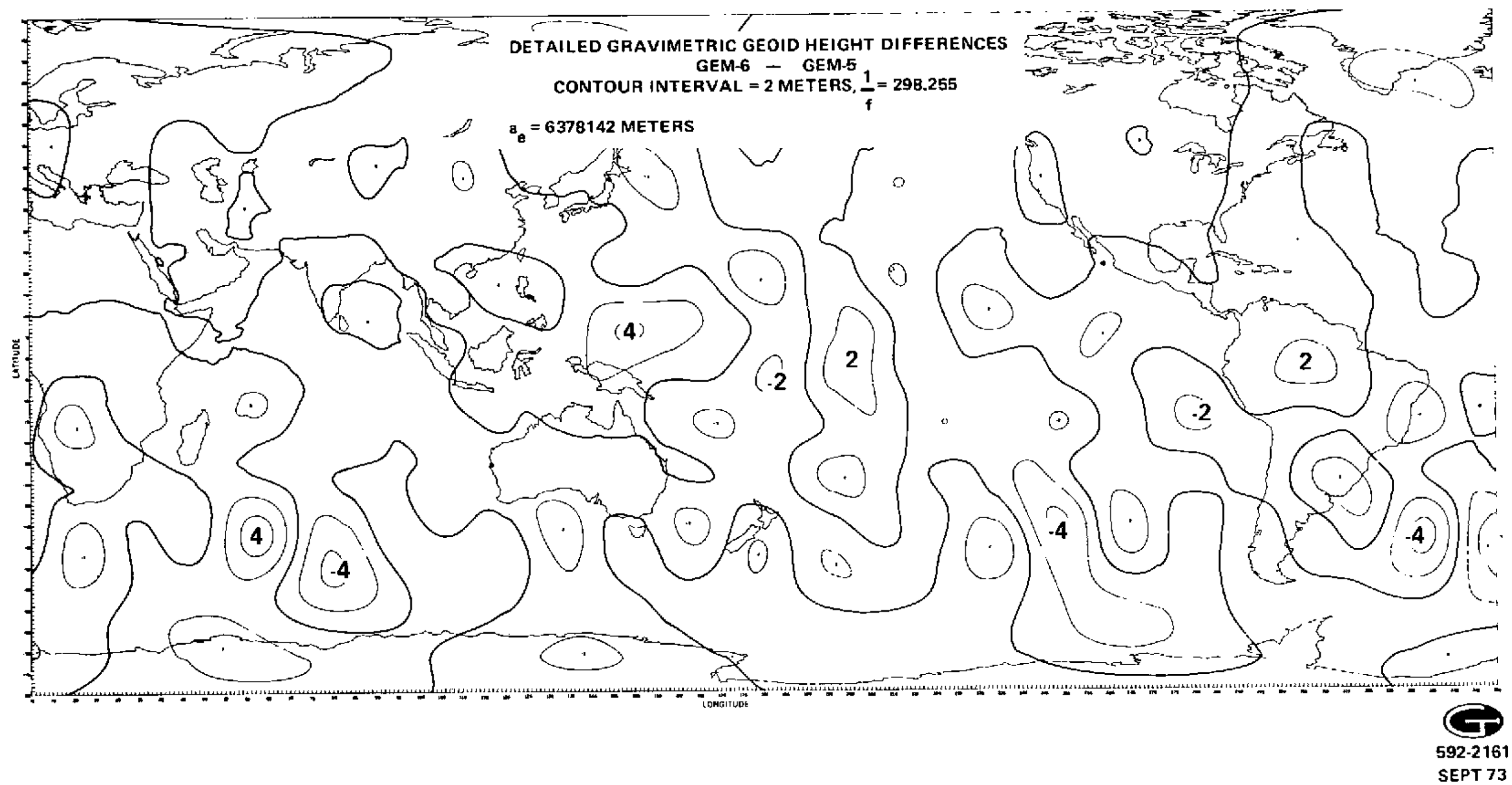
Figure 6.



DETAILED GRAVIMETRIC GEOID HEIGHT DIFFERENCES
GEM-6 — GEM-5
CONTOUR INTERVAL = 2 METERS, 1/f = 298.255
a_e = 6378142 METERS
(4)
-2
2
2
-2
4
-4
-4
-4
-4
LATITUDE
LONGITUDE
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Figure 7.

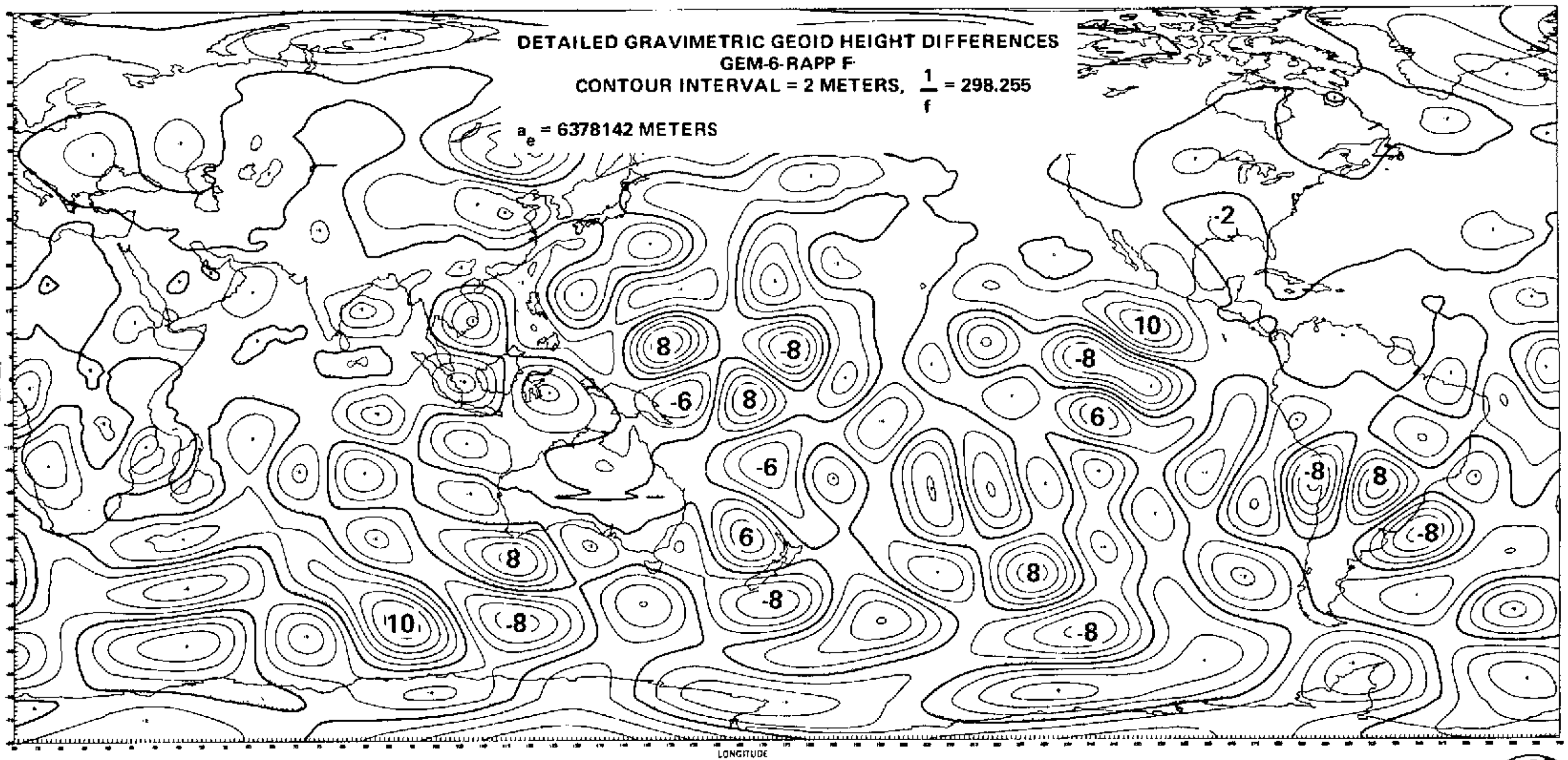

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Figure 8.

HISTOGRAMS OF GEOID HEIGHT DIFFERENCES

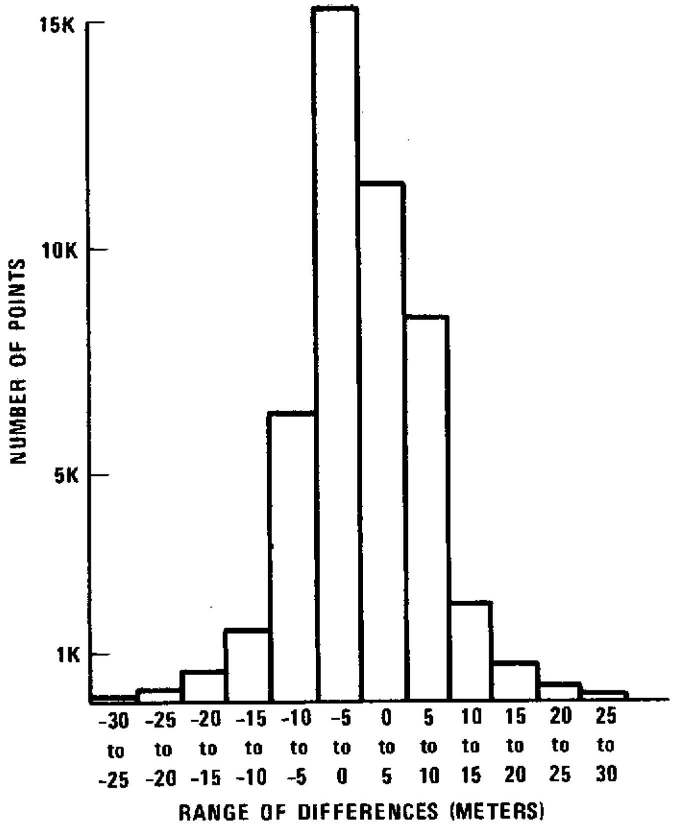

Figure 9.1. GEM 6 vs. SAO III

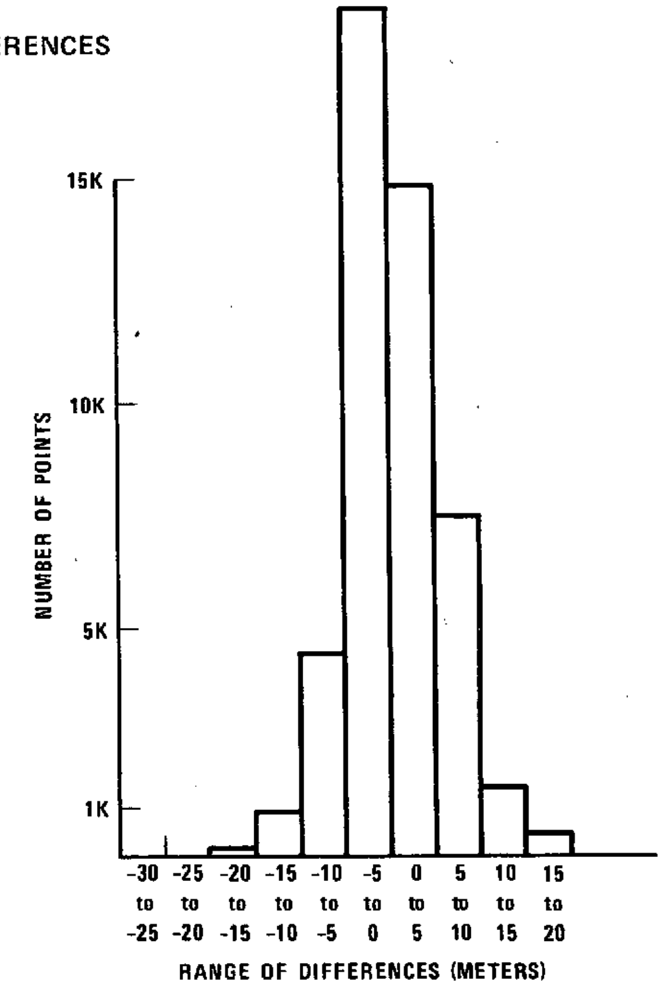

Figure 9.2. GEM 6 vs. SAO II

HISTOGRAMS OF GEOID HEIGHT DIFFERENCES (Continued)

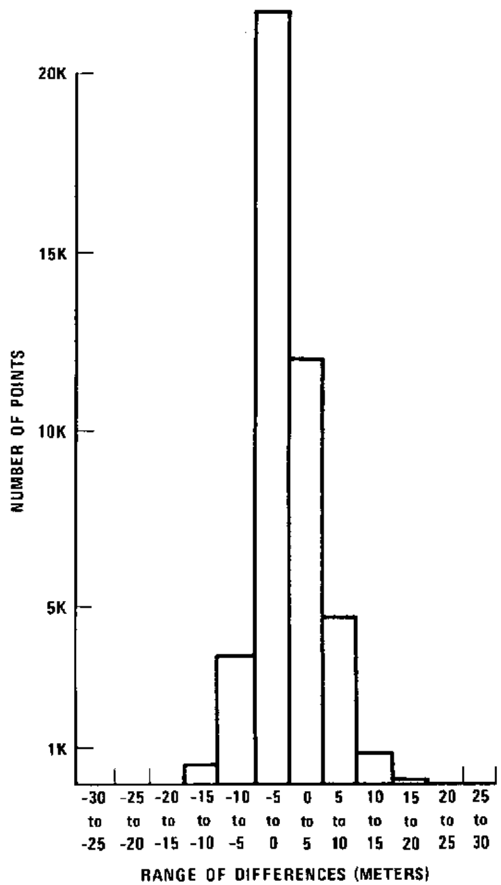

Figure 9.3. GEM 6 vs. GEM 4

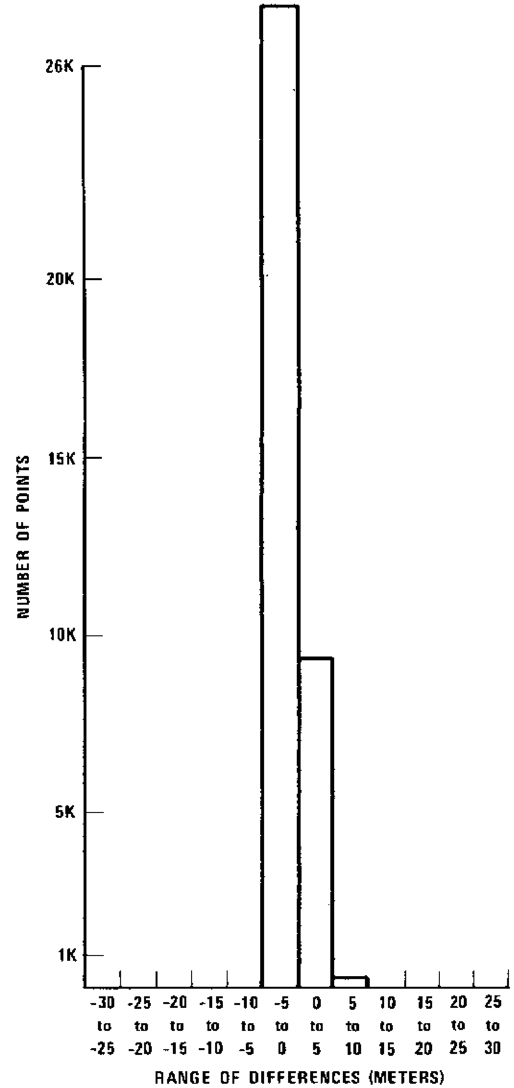

Figure 9.4. GEM 6 vs. GEM 5

HISTOGRAMS OF GEOID HEIGHT DIFFERENCES (Continued)

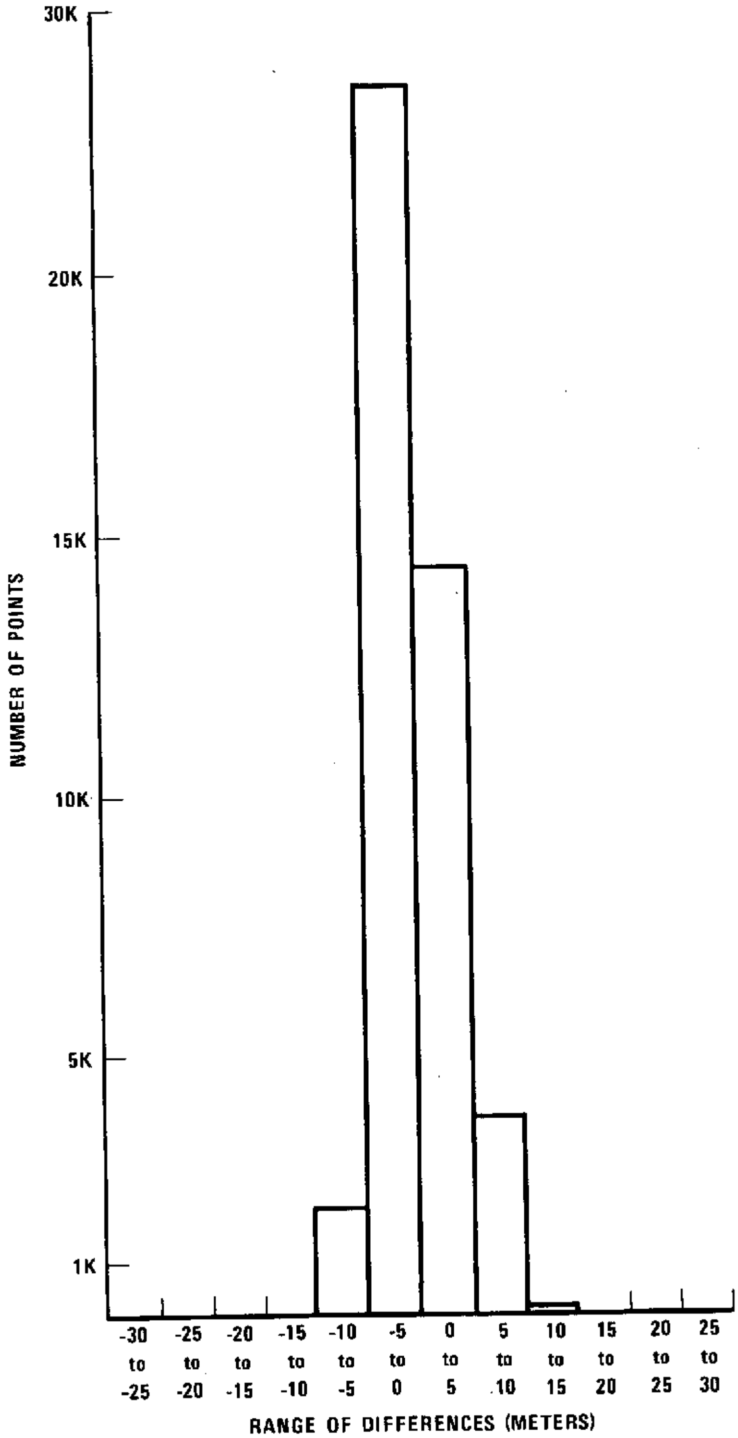

Figure 9.5. GEM 6 vs. RAPP

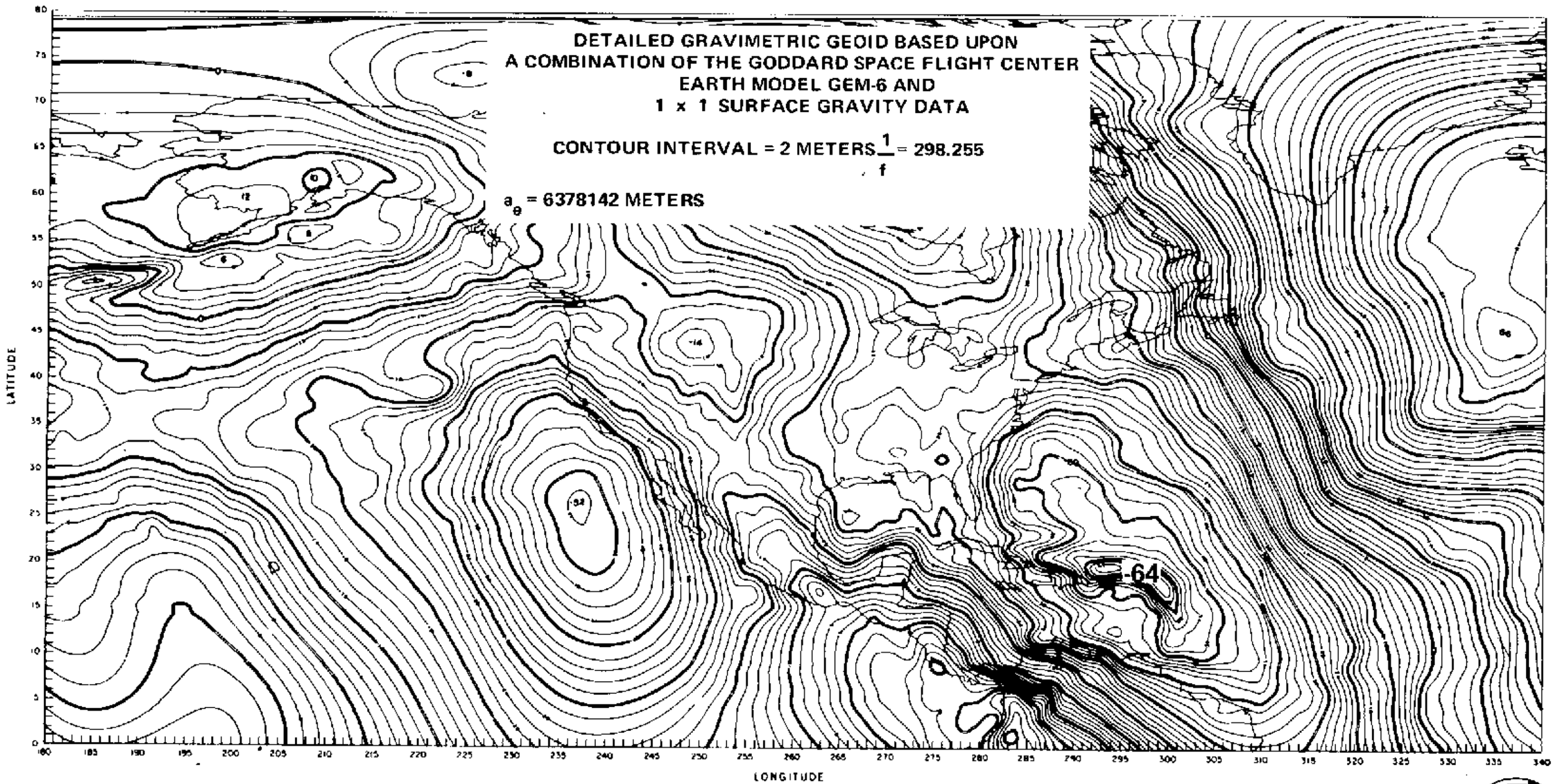

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Figure 10